The e/p Option in the 3 TeV Booster

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I. Introduction

While the eventual aim of the VLHC experimental program is the construction of a large circular hadron collider, this machine would require an injector, and a significant experimental program could take place in the tunnel of the 3 TeV injector. This note considers the costs and benefits of colliding leptons on hadrons.

II. Physics goals at the ep collider

Lepton-hadron deep inelastic scattering (DIS) experiments have played important roles in development of the Standard Model. The discovery of partons inside the nucleon and weak neutral currents occurred in (nowadays) low-energy DIS, and more recently low-energy DIS in fixed target experiments have been used for increasingly precise measurements of the strong coupling constant , α_S, and the electroweak mixing angle, $\sin^2\theta_W$. When the HERA collider, operating at $\sqrt{s}$ ~ 300 GeV, extended precise measurements of the proton's internal structure up two orders of magnitude in momentum-transfer (Q^2), or equivalently down two orders in parton-momentum-fraction x, theoretical interest was sparked many areas of Quantum Chromodynamic (QCD). These include investigations of perturbative QCD in exclusive and inclusive processes, at the interface of pertubative and nonperturbative interactions, in diffractive and non-diffractive scattering, into regions where there are two-or-more hard-scales, and so on. The relatively high center-of-mass also allowed tests for new phenomena beyond the Standard Model, that were competitive or complementary to searches performed at e^+e^- and $p\bar{p}$ colliders.

A new *ep* collider with $\sqrt{s}$ ~ 1 TeV would provide a unique method to continue and enhance this rich program. A partial list and short description of a fraction of the physics that could be done at this new facility is contained in the next three subsections. Before describing the physics, it should be noted that the experiments/detectors at this collider do not require any great technological improvements compared to present detectors at HERA. Furthermore, lessons learned at the present experiments could be used to optimize the design of the new detectors taking full advantage of technological advances that have occurred in the recent past since HERA was commissioned.

IIa. QCD and the Structure of the Proton

The *ep* collider is first and foremost a QCD-factory - designed to provide a multitude of interesting inclusive and exclusive measurements relevant to the test and improvements of our theory of hadron interactions. Compared to HERA, the new collider will extend measurements of the proton structure functions up by a factor of ten in both Q^2 and/or $1/x$. The covered kinematic reach also nicely overlaps with some of the (x,Q^2) region at HERA providing immediate and necessary cross checks of absolute cross sections and structure functions measured. The extension into higher Q^2 will allow more precise measurements of α_S by reducing sensitivity to systematic uncertainties that are predominant at low-Q^2.

In the early days of the new collider, the experiments can concentrate on exploring the interface of perturbative-to-nonperturbative physics at very small-x. The wide-band-beam of real and virtual photons colliding with the proton will allow extension of inclusive measurements of total, diffractive and inelastic cross-sections to three-times higher center-of-mass than now possible. New measurements of the photon structure function to lower-x than possible at any other collider.

Proton structure functions will be measured over the extended kinematic range. There may be a chance to reach a low-enough x at large-enough Q^2 that the parton densities will become saturated, and the first effects of non-linear dynamics in gluon interactions can be explored quantitatively. The ability of QCD to properly describe the parton density distributions in the new kinematic region will be severely tested, and may lead to insights on the proper evaluation of QCD evolution -- so called "BKFL vs DGLAP" dynamics.

The event rate at $Q^2 > 1000$ GeV^2 will be roughly a thousand times that at HERA, and so it should be possible (using combinations of electron and positron beams) to measure both F_2 and xF_3 cross sections with vastly improved precision. This enables one to determine the parton distributions separately for each flavor of quark and anti-quark. It is likely that such precise data will be needed by the groups operating at LHC and its successors in order to evaluate their QCD background and physics rates.

IIb. Electroweak physics

Unlike at HERA, where the cross-sections and event rates for Charged Current reaction (W-exchange) are minuscule compared to Neutral Current (Z and virtual photon exchange) - at this new facility event rates of > 100,000 NC and CC per year for $Q^2 > 10000$ GeV^2 are expected. In addition to the precise measurements of F_2, xF_3 mentioned above, this non-trivial event rate for electroweak scattering opens up the possibility for Electroweak measurements in both DIS and in direct production of the weak-vector bosons. For instance, details here (must confirm sensitivity)

Secondly, it is likely that by the time this collider is operational, the limited factor in sensitivity to fundamental parameters (weak-couplings, weak-mixing angles) in certain direct measurements at hadron colliders, will be due to uncertainty in the (anti)proton's parton structure. Improvements by large factors compared to present data are inevitable if the data from this collider are available to constrain the quark/anti-quark/gluon densities of the proton.

IIc. Searches for new physics

It is generally true that the sensitivity to directly produce new particles is greatest in colliders achieving the highest center-of-mass per collision. Therefore, a $\sqrt{s} = 1$ TeV *ep* machine is at some disadvantage to the LHC in absolute "mass reach" for new particles. Nevertheless, for some selected channels, particularly those with leptons in the final state, or with lepton-flavor violation in the production mode, the mass reach is comparable for the proposed machine and for LHC. More crucially, should a new particle, such as a LeptoQuark, with mass less than ~600 GeV be discovered at LHC or during the Tevatron Run II, then the proposed machine will be an ideal "factory" for producing and understanding the particle's interactions. For instance, combining data from electron and positron scattering, especially if polarized interactions are possible, would allow one to disentangle the spin-isospin-flavor quantum numbers of a singly produced leptoquark or squark.

The proposed machine does have some advantage for discovering 'new interactions' that do not result in mass-resonances, but instead lead to changes in the observed distributions of high-mass final states {Such as "contact interactions" or quark/lepton-compositeness}. Firstly, discovery limits for such interactions depend crucially on accurate and precise predictions for the standard model "background" cross-sections. These background distributions typically rely on estimates of 'parton distributions' in kinematic regions where such have not been directly measured and where some (in particular gluon-density distributions) are not precisely constrained. Because on parton in the *ep* collision is the 'structureless' lepton, sensitivity to parton distributions is smaller than at *pp* colliders and background predictions usually better constrained by previous measurements. In fact, measurements of structure functions here may even reduce the uncertainties at hadron colliders and thereby eliminate a fundamental limitation of their sensitivity to some forms of new physics and interactions.

III. A Large e^+e^- Circular Top Factory

In addition to the ep options, an electron/positron injector chain would permit the eventual construction of a large circular e^+e^- collider in the VLHC tunnel, which could be used to produce large numbers of $t\bar{t}$ pairs or light Higgs. A preliminary design of this option has been produced and published in the Proceedings of the Snowmass workshop and the 1997 Particle Accelerator Conference.

IV. Collider Requirements

The ep collider would would face many of the problems of HERA, although at beam energies three times higher. A total power consumption limit of 50 MW would correspond to an electron beam of about 80 GeV, giving $\sqrt{S} \sim 1$ TeV. The dimensions of the 34 km tunnel for the 3 TeV collider are roughly comparable to the 27 km LEP tunnel, so magnets and rf could be scaled from this machine.

The performance of the collider must be sufficient to produce a physics program complementary to the LHC and other machines which will be operating in 20 years. This facility should have high luminosity and the flexibility to be study the complete range of available physics. This effectively means that the luminosity of the collider will have to permit counting rates on the order of one fb^{-1} per year. In addition it will be necessary to be able to look at both e^+/p and e^-/p collisions. This will require an injector chain that can produce both polarities, requiring either that ring magnets are reversed or injection and extraction systems for both polarities are provided. A further requirement of the ep program would be that the operation of the machine would be compatible with lepton polarization. Since the Sololov-Ternov times, $\tau_p^{-1} = 5\sqrt{3}\ \gamma^5\ \hbar\ e^2 /\ 8\ \rho^3\ m^2\ c^2$, are on the order of 30 minutes for beams of 80 GeV, operation with polarization seems possible. The design of the lattice must also be compatible, however, with spin rotators incorporated into the design from the beginning.

Experimental access to the beam must also be provided for small angle (low Q^2) events. These counters would be located in both the proton and lepton lines and, at HERA are inserted almost into the halo of the beam. Since the events have a large cross section and counting rates, these measurements can be carried out in the early stages of the experimental program before the machine reaches full luminosity and special tunes can be used, for example to move the interaction point up or downstream where detection would be easier.

V. Injector Chain

It will be necessary to adapt the Fermilab injector to provide high energy leptons. This could be done as shown in Fig 1. The system consists of: 1) a new e+e- linac system. 2) an accumulator ring for positrons, 3) A lattice correction package, together with a new injector and extraction system for the Booster, 4) and beamlines to carry the beams to and from the Main Injector.

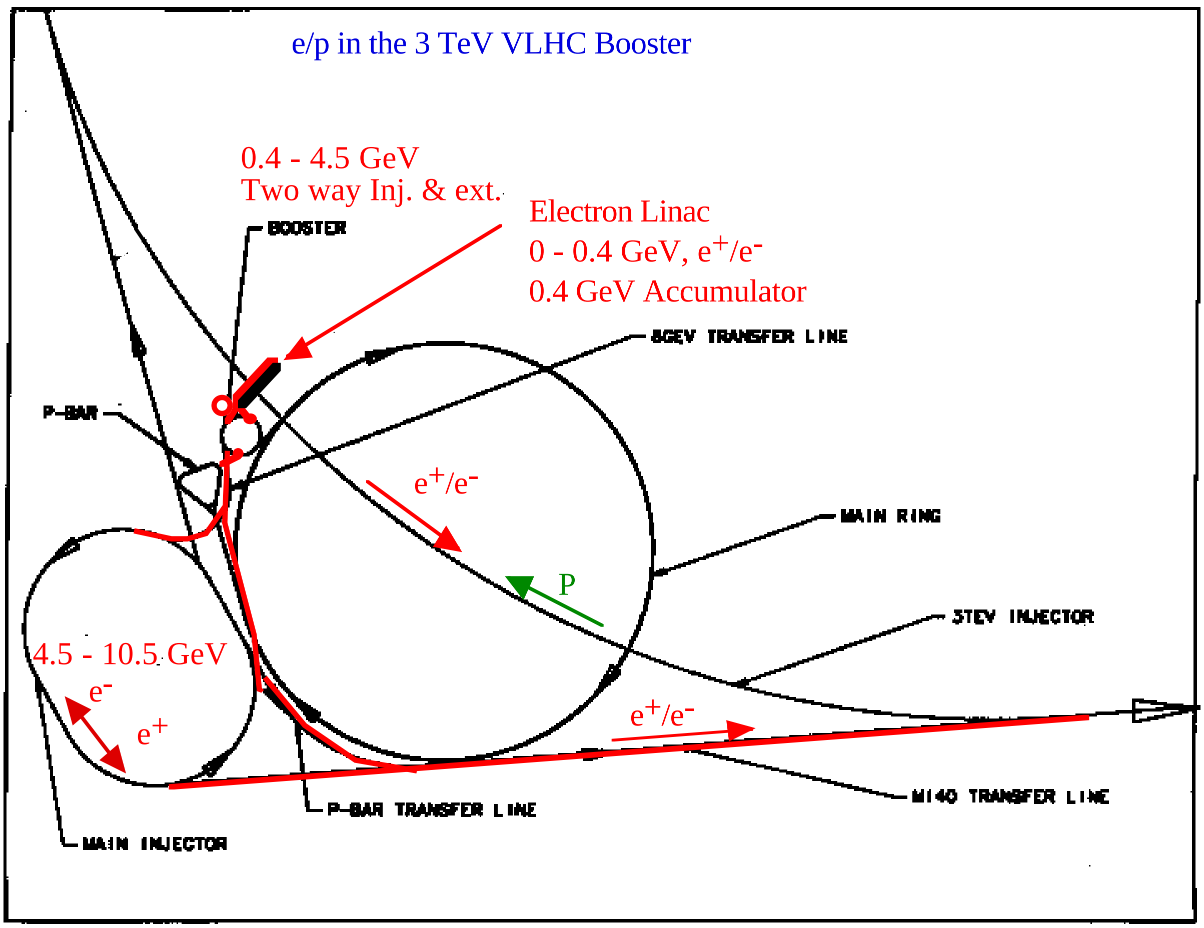

Figure 1. The injector chain for an e/p collider.

The electron linac would be based on those at DESY, CERN and the Argonne APS. There seems to be sufficient space in the present proton linac vault to construct an electron linac and the klystron gallery also has sufficient space for the electron linac power supplies, however the positron accumulator would require a new shielded room.

It is assumed that the Booster would operate from 0.4 to ~ 4 GeV, and the Main Injector would accelerate leptons from ~4 to ~10 GeV, the energies being determined by the requirements that the existing rf system provide the power required to replace synchrotron loss. More rf could be provided at a cost of ~0.7 $/V if needed, however it is not clear that the low injector energies introduce problems. The injection fields for both the Booster and Main Injector would be about half of the design fields for these machines. The magnets of the Main Injector have been measured and should be adequate at these field levels, and it is assumed that the Booster would also be able to operate in this mode, since the required aperture at low energies should be small. Synchrotron radiation problems such as heat removal and radiation doses have not yet been considered.

It will be necessary to provide correction packages to control the damping partition numbers in the Booster. These packages would consist of gradient magnets, dipole magnets and quadrupoles which would compensate for the effects of the alternating gradient lattice. These packages should be on the order of 5 - 8 m long and could be distributed among the five empty long straight sections.

The costs of modifications to the injector chain seem to be primarily in the new linac and accumulator ring, and in the new injection and extraction systems for the booster. It is unclear what modifications required for synchrotron radiation in the Booster and Main Injector would cost.

VI. Services

Additional services must be provided to the 34 km circumference injector due to magnet cooling and the removal of synchrotron radiation power. Ultimately the most of the 50 MW of power produced by the rf system appears as heat at the outside edge of the vacuum chamber. The usual solution to heat removal would be to provide cooling towers at intervals around the ring, however the superconducting magnets require no comparable services. Synchrotron radiation would also produce radiation doses of 10^6 - 10^8 rads/yr (depending on location) due to the high energy part of the synchrotron photon spectrum. This dose could damage insulators and cause a variety of problems. The radiation dose can be absorbed by local lead shielding.